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A STUDY OF ALTERNATIVE DESIGNS FOR A SYSTEM
TO CONCENTRATE CARBON DIOXIDE
IN A HYDROGEN-DEPOLARIZED CELL

A Report Prepared for the
National Aeronautics and Space Administration
Washington DC
on Contract No. NASw-2439

Prepared by
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January 1973

1. INTRODUCTION

1.1 BACKGROUND

The National Aeronautics and Space Administration, Headquarters, has contracted with the Society of Automotive Engineers, Inc., on NASA Contract No. NASw-2439, for studies of specific problems relating to advanced life-support systems for spacecraft. These studies have been assigned by the Society of Automotive Engineers to its Bioenvironmental Systems Study Group, which functions under the cognizance of SAE Committee SC-9, the Spacecraft Environmental Systems Committee, of which Dr. Jack M. Spurlock is the Chairman. This report documents the results of a study performed on this contract by the Study Group to review alternative designs for a hydrogen-depolarized cell to concentrate carbon dioxide in spacecraft atmosphere-control systems.

Recent research and development has identified a hydrogen-depolarized cell concept which has shown good potential for markedly improving the process of CO₂ removal from spacecraft atmospheres and controlling the atmospheric humidity during the flight mode. It offers an interesting opportunity for trade-off studies against baseline methods presently being considered for use in NASA's manned missions in space. Two NASA contractors, Life Systems, Inc., and the Hamilton Standard Division of United Aircraft Corp., are now performing advanced development work on

the hydrogen-depolarized cell concentrator method. The specific objective of the study described in this report was to review progress and technical results accomplished to date by these two contractors, and to formulate recommendations to NASA on: (1) the relative progress that has been accomplished; (2) the nature and extent of significant technical problems which remain unsolved; (3) methods of solving these remaining problems; and (4) the relative status of the two development efforts with respect to readiness for commitment to prototype design and production, including system trade-off features for each.

A group of experts in the interrelated fields of electrochemistry, chemical process engineering, and spacecraft life-support systems engineering was selected by the Society of Automotive Engineers and given the responsibility to accomplish this study. The members of the Study Group were:

Dr. Jack M. Spurlock
T. A. Jonas/Associates (Consultants)
(Principal Investigator for the Contract)

Dr. H. P. Meissner
Massachusetts Institute of Technology

Dr. L.W. Ross
University of Denver

Dr. J.H. Strohl
West Virginia University

Career resumes for these members of the Study Group are included in the Appendix of this report.

1.2 METHOD OF PROCEDURE

The Study Group accomplished its assigned task by convening a series of meetings in which the Group was either briefed by NASA and contractor representatives or it deliberated the problem privately. During the first of these sessions, the Group met with NASA representatives from Headquarters and NASA Ames Research Center to receive thorough briefings on the background of the development programs to be studied and their current status. During the second session, the Group met with representatives of the Hamilton Standard Division (HSD) of the United Aircraft Corporation, at their facility in Windsor Locks, Connecticut, and was briefed on HSD's technical approach, steps in fabrication and testing, test results to date, and systems engineering. During the third session, the Group met with representatives of Life Systems, Inc. (LSI), at their facility in Cleveland, Ohio, for the same type of briefing. At the meetings with the contractors' representatives, members of the Study Group discussed technical factors with these representatives, in great detail, to elucidate the factors involved, the state of the technology, problem areas and approaches being considered for their solution, systems engineering considerations, and prospects for the success of an engineering prototype design and production program.

During the remaining sessions, the Study Group met privately and thoroughly reviewed the information it had received,

contractors' reports and other technical literature, and all other pertinent aspects of the matter. Recommendations were formulated which were considered to be in NASA's best interest. The principal factors that were derived from the Study Group's observations and analysis, and which served as the basis for the Group's recommendations, are summarized in Section 2 of this report. The essential conclusions and recommendations are summarized in Section 3.

2. RESULTS OF ANALYSIS

This section reviews the principal factors involved in the Study Group's analysis of the present status of the two alternative designs for a CO₂ concentrator, both of which are based on the same electrochemical process using a hydrogen-depolarized cell. No details of the electrochemical theory which forms the basis for these designs are included in this report; these details, together with background information on the development of these designs, are adequately presented in the numerous NASA contractors' reports and technical papers which have been published on this subject.

Based upon the briefings provided to the Study Group by the NASA representatives and the contractors' representatives (from Life Systems, Inc., and Hamilton Standard), visits by the Study Group to the contractors' laboratories, and a review of available reports, etc., the Study Group identified the following key factors for a comparison of the contractors' technological status:

1. Control method: The choice of control method is integral to the basic design concepts and their differences. LSI uses a constant-current controller and varied cooling-air flow rate to control exit air temperature and maintain electrolyte balance. HSD uses a high air flow rate through the cells and a variable (ballast) resistor for manual current control. It is expected that poor current control would lead to potentially adverse changes in the moisture balance of the cells, especially when air flow-rates are high (HSD design). Therefore it appears that better electrolyte

balance (stability) would be achieved by the automatic constant-current controller.

2. Moisture balance across air passage: HSD's flow rate of 7 fps is used to keep the cell temperature down (heat removal), but it could lead to marked sensitivity to moisture/electrolyte balance. The difficulty of precise measurement of such effects at points within the cells has led to poor understanding of the problem. LSI recognizes the problem and importance of moisture balance and is trying to gain an understanding of the factors involved.
3. Current density in cells: HSD = 15 amps/ft²
LSI = 20 " "
4. Cell assembly: HSD has removable cell pairs; LSI has isolatable cell stacks. NASA's definition of maintainability will have to be the key to this issue. This is not a decision factor for the Study Group.
5. Relative equivalent sub-system weight: Can now only be compared on a very dissimilar basis--LSI is just now in the process of optimizing its subsystem's weight for the SSP application, whereas HSD has already accomplished this task. NASA should carefully compare the unit cell weights (considering LSI's need for a metal heat sink) separately from the peripheral equipment weight and estimate LSI's ability to reduce the weight (and volume) of the latter, or recommend a waiting period to see how LSI does on its SSP subsystem optimization study.

6. Plastic versus metal cell construction: The plastic cell components used by LSI do not seem to require machining, and are probably cheaper and easier to mass produce. There probably will not be a materials compatibility problem for the plastic for the SSP atmosphere, but this should be checked through NASA; one should also consider possible reduced life of the plastic and efficiency of heat conduction out of the cell (LSI must use metal heat sink). There doesn't appear to be a major problem for comparison unless there is an apparent performance-degradation or fire-hazard problem with the plastic, which appears unlikely.
7. Quality control for electrolyte material: LSI has not experienced the trace-contaminant problems with cesium carbonate electrolyte reported by HSD, although LSI has conducted more extensive testing. Has LSI simply worked with a purer source at the outset, or is there some other problem unique to the HSD unit design?
8. Transport mechanism within the electrolyte: HSD seems to be quite concerned about bicarbonate ion transport, and this has led to a search by HSD for a different electrolyte. LSI is running some extra tests on this, but thus far they have not found the controlling mechanism to reside within their electrolyte; nevertheless, they are aware of the possibility of bicarbonate transport effects. It would seem that rate-controlling mechanisms will more likely occur at phase boundaries rather than within phases. Diffusion in solution is very slow, and at a thickness of 0.02 inch in the cells it may be limiting. It is quite possible that

HSD may be operating at too high a current, perhaps leading to precipitation of the bicarbonate, or at least to lower efficiency. This needs to be explored more thoroughly.

9. Relative technology base: LSI has performed more extensive testing and has a significantly longer period of experience; their testing has included various scale sizes. In addition, LSI appears to have demonstrated better technical awareness of testing methods and insight to the "science" involved in problem seeking and solving. The LSI team seems to have more directly related technical backgrounds and expertise assigned to the design and development task.
10. Combined humidity control and CO₂ concentrator: HSD has been working on the development of such a combined unit; LSI has not. In some NASA applications this combined configuration will probably have some advantages. However, because both contractors were not working on this concept, the Study Group could not compare approaches to such a design. In general, the CO₂ concentrator designs offered by HSD and LSI appear to be able to interface well with existing types of humidity-control units, and both could probably equally well be configured as a combined unit; HSD's cell design approach does not appear to offer any particular advantages in this respect.
11. Effect of CO₂ level of operation in spacecraft: Although both teams have looked at design factors for operation at lower CO₂ levels (below 3 mm of Hg), it appears that LSI will have some distinct advantages in capability and awareness of technical factors involved

to achieve such operation, should NASA medical decisions impose this requirement in the future. This lower CO₂ partial pressure region is the very domain where mass-transfer-controlling limitations are encountered (ref. Fig. 22, NASA CR 114426, March 1972), and LSI already has a very reasonable plan for studying this domain; it appears that HSD has not yet confronted this problem.

12. Testing methodology: The LSI "trend and fault analysis" instrumentation is a very effective test aid, and permits good diagnosis of performance problems and performance evaluation in detail; it is also a very flexible tool for design experimentation (scaling studies, etc.). Both LSI and HSD are seriously lacking in test experience with real man-metabolic products, including contaminants, and real CO₂ duty cycles and rates. HSD has only run a simulated CO₂ duty cycle analysis through their computer simulation model.
13. Hydrogen leak detection methodology: Both HSD and LSI use a type of cupola design for hydrogen catching and sensing. These appear to be extremely sensitive to zero-G effects. The cupola area must be boxed in and suction must be applied to provide effective forced-convection sampling of the hydrogen against the zero-G free-convection effects.
14. Cell-efficiency criteria: Both the HSD and the LSI criteria are not completely satisfactory. LSI's "transfer index" does not provide an adequate basis for efficiency analysis or comparisons. The HSD criterion of K in their equation for "cell efficiency" seems to be based on an Ohm's Law interpretation of the system such that

flux is proportional to driving force; but then instead of using the difference in CO_2 partial pressures as the driving force, they use a single-point PCO_2 , which makes interpretation of the resulting numbers very difficult (and perhaps virtually meaningless). It would appear that a ratio of theoretical work to measured energy would be the better, consistent choice for both systems, as a baseline comparison factor. A consistent criterion for comparing performance efficiency must be established or each contractor will be able to use some criterion that favors his own system.

15. Miscellaneous factors to be considered:

- a. The reason for HSD's detailed attention to porosity of the catalytic surface and Teflon film barrier, while LSI has not identified this as a significant factor.
- b. LSI's observation of slow return to best cell performance, following shutdown; no mention by HSD.
- c. LSI's observation of slow decline of cell efficiency (by their criterion of measurement) to $\text{TI} = 2.3$; no mention by HSD.
- d. LSI has identified exit temperature and cell-voltage decline as an indication of improper hydrogen supply.

3. CONCLUSIONS AND RECOMMENDATIONS

Based upon the material presented in Sections 1 and 2 of this report, the following conclusions and recommendations have been formulated:

1. At present there is not an adequate basis for selecting one cell-design over the other. Data are not available, on the same basis, to permit a reliable determination of relative efficiencies, reliabilities, maintainability, and performance variation with time. LSI certainly has demonstrated greater achievement in its results to date, but there are some remaining puzzling effects to be clarified and additional data are needed to permit a fair evaluation of prospects for success in the system application of this method.
2. Neither contractor is using an efficiency criterion which is completely effective in portraying performance. A single, common and meaningful criterion should be used by both contractors to permit such a characterization of performance and to permit a reliable comparison of performance for the two competitive designs. The Study Group recommends the use of a chemical thermodynamic efficiency criterion (commonly used in industrial chemical process analysis) in the form of a factor of merit, F_m , viz.:

$$F_m = \frac{\text{amount of CO}_2 \text{ removed per unit of time}}{\text{total cooling duty (BTU) per unit of time}}$$

where the cooling duty would include hydrogen enthalpy and fan energy. This, in effect, would identify the amount of CO₂ removal

that has been accomplished for a certain amount of power expenditure required to achieve this removal. One desirable refinement might be the conversion of the numerator of the above expression into theoretical energy units so that the criterion becomes dimensionless, with a value for F_m in the range from 0 to 1. Such a conversion could be accomplished simply by employing the free-energy definition ΔG° , for example.

3. Both contractors should run some additional long-term tests, measuring specified variables under exact and controlled experimental conditions. The purpose of these tests would be the formulation of a complete material balance for the cells. This would permit a clear comparison, on the same basis, of both cell designs using comparative graphical representations of cell voltage and the ratio of CO_2 transfer rate/ O_2 utilization, both as functions of cell current for various periods of run time. These tests should be conducted under conditions of constant, uninterrupted source of power, gas flow, etc. If possible, the tests should be conducted at the same values of inlet gas flow rate, temperature, pressure, dew point, PCO_2 , etc. The inlet should be preceded by an activated carbon column for 60 days (to remove trace contaminants that might prevent an identical basis for comparing system performance), then the column should be removed from the test system to see if there are any performance perturbations in the cells. Flow rates, temperatures, pressures, dew point and composition of principal

reactants for each inlet and exit stream should be measured daily for the first 30 days, then every 5 days thereafter (at least that often). Also during the period of these tests an accurate log of reliability and maintenance experience should be kept (cell repair, replacement, downtime, etc.) and reported. Data should also be plotted as \bar{E}_m versus time and cell voltage versus time. The total run time should be at least 90 days, under these specified conditions.

4. There should also be some simulation of actual diurnal variations of PCO_2 in the inlet gas stream in separate tests for 30 days. These will identify effects on electrolyte balance of variations in CO_2 loading under essentially realistic operational conditions.

Items of New Technology that are Needed

Several items of new technology also were identified by the Study Group as subjects of further research to serve as the basis for future improvements in hydrogen-depolarized cell design and performance. These are summarized below.

1. Improved Electrolyte Materials. - Higher rates of CO_2 transfer could be realized if higher concentrations of CO_3^{2-} and HCO_3^- could be tolerated by the electrolyte matrix without the formation of precipitates. One potentially promising method of achieving this is the use of mixed cation electrolyte materials. A simple equilibrium calculation shows that a mixed cesium, rubidium, potassium electrolyte composition would permit bicarbonate ion concentrations that are 10

per cent higher than for cesium alone. In addition, there might be an advantage to using fluorides or sulfates rather than carbonates. Fused salt electrolytes also should be considered. For example, $\text{Cs}_2\text{SO}_4 \cdot \text{FeSO}_4 \cdot 6\text{H}_2\text{O}$ melts at about 70°C , and mixtures could therefore be expected to melt at lower temperatures. At elevated temperatures the CO_2 transfer rate would be higher and precipitation would probably not be much of a problem. But this would require a complete study of the fused-salt systems (including characterization of water vapor pressure versus temperature and composition, carbonate solubility, etc.).

2. Improved Understanding of Transport Mechanisms. - It is clear that the controlling mechanisms for ion transport in the hydrogen-depolarized cells are not well understood. These will have to be elucidated before approaches to the improvement of cell performance and reliability can be formulated in a scientific manner. There should be some parallel fundamental research on the roles of carbonate and bicarbonate ions, as well as any other possible ions, in the CO_2 transport mechanism. It is possible that bicarbonate electrolytes would be more efficient than carbonates, if pH were properly controlled.

3. Systems to Maintain Lower PCO_2 Levels. - Present CO_2 removal systems appear to be reaching diminishing returns with respect to achieving lower CO_2 levels in the spacecraft environment; i.e., efficiency decreases as lower levels of CO_2 are demanded, and cost and weight penalties tend to increase more than linearly. Advanced research

could address its emphasis to the development of a "new" system that has a high capacity at low outlet CO_2 concentrations, or alternatively, the development of a low-capacity system that is very efficient for CO_2 removal and that can be used in series with present systems as a "vernier" concentrator.

4. Hydrogen Detection Instrumentation.- Because of the importance of hydrogen as a reactant in life-support systems such as the hydrogen-depolarized cell, the detection of hydrogen leaks under zero-gravity conditions deserves more attention. One possibility would be the use of a small quadrupole or cyclodal mass spectrometer that sequentially samples potential trouble zones by a tubing "distributor" network for drawing samples. This would be particularly attractive for missions on which a mass spectrometer could be used for other purposes (Space Shuttle Sortie Lab experiments, etc.).

5. Electrode Reliability Analysis.- Electrodes will probably poison eventually and fail. Typical lifetimes to failure and reason(s) for failure should be characterized to establish life expectancy and reliability trends. To achieve this, electrodes should be tested until failure occurs, followed by research to determine the exact reasons for each failure and methods by which the failure could have been prevented (or corrected after failure). It is quite likely that such tests will require the use of air that has actually been contaminated by metabolic products exhaled by human subjects. This would be an excellent adjunct to long-duration manned chamber tests in the future, Space Shuttle Sortie Lab experiments, etc.

APPENDIX

CAREER RESUMES FOR STUDY GROUP MEMBERS

- A. Dr. Jack M. Spurlock
- B. Dr. H. P. Meissner
- C. Dr. L. W. Ross
- D. Dr. J. H. Strohl

A. BIOGRAPHICAL DATA FOR DR. JACK M. SPURLOCK

Education

B.S., Chemical Engineering, University of Florida, 1952
M.S., Chemical Engineering, Georgia Institute of Technology, 1958
Ph.D., Georgia Institute of Technology, 1961

Experience

Theodore Jonas and Associates -- Systems engineering and government relations consultant, 1971 to date.

Health and Safety Research Institute -- Executive Vice President and Director of Research, 1969-1971.

Atlantic Research Corporation -- Director of the Engineering Research Department, 1964-1969.

Martin Marietta Corporation -- Manager of the Aerosciences Research Department, 1962-1964.

University of Florida -- Adjunct Professor of Engineering, 1963-1964.

Georgia Institute of Technology -- Research Associate and Assistant Professor, School of Chemical Engineering and Engineering Experiment Station, 1955-1962.

Auto-Lite Battery Company -- Process and Quality Control Engineer, 1954-1955.

Professional Activities

Chairman of Environmental Control and Life Support Systems Committee (SC-9), Society of Automotive Engineers.

Newsletter Editor for Heat Transfer and Energy Conversion Division, American Institute of Chemical Engineers.

Fellow, American Institute of Chemists, and Professional Chemist - Accredited.

Associate Fellow, American Institute of Aeronautics and Astronautics.

Member of Sigma Xi.

Member of Aerospace Medical Association.

Member of American Association for the Advancement of Science.

Professional Activities - (continued)

Member of American Chemical Society.

Member of the Biomedical Engineering Society.

Member of Southern Medical Association.

Member of American Society for Engineering Education.

Member of the Association for the Advancement of Medical Instrumentation.

Guest lecturer for numerous university graduate seminars in systems engineering, biomedical and safety engineering, and environmental engineering, nationwide.

Publications

Approximately 40 articles and reports in the fields of spacecraft systems engineering, aerospace safety, aerospace medicine, transport phenomena, environmental affects, combustion, and biomedical engineering.

Co-author, with Dr. T. W. Jackson, of a book "Research and Development Management", published by Dow Jones-Irwin.

Awarded patents for biomedical engineering devices.

B. BIOGRAPHICAL DATA FOR DR. HERMAN P. MEISSNER

Education

B.S., Chemical Engineering, Massachusetts Institute of Technology, 1929
M.S., Chemical Engineering, Massachusetts Institute of Technology, 1930
Sc.D., University of Frankfurt am Main, Germany, 1938

Experience

Massachusetts Institute of Technology --

DuPont Fellow in Business and Engineering Administration, 1932-1933.
Instructor, Business and Engineering Administration, 1934-1936.
Instructor, Chemical Engineering Department, 1938-1940.
Assistant Professor, Chemical, Engineering Department, 1940-1943.
Associate Professor, Chemical Engineering Department, 1943-1951.
Professor, Chemical Engineering Department, 1951 to date.
Executive Officer, Chemical Engineering Department, 1970 to date.
Lamont du Pont Professorship, 1970 to date.

Professional Activities

Consultant, Chemical Corps, U. S. Army, 1950-1955, Special Committee, Saline Water.

Member of American Institute of Chemical Engineers.

Member of American Chemical Society.

Member of American Academy of Arts and Sciences.

Member of Sigma Xi.

Publications

Approximately 40 articles and numerous patents.

Joint Author: "Advanced Thermodynamics for Chemical Engineers", 1958.

Author: "Processes and Systems in Industrial Chemistry", 1970.

C. BIOGRAPHICAL DATA FOR DR. LAURENCE W. ROSS

Department	Chemical Engineering, University of Denver
Academic Rank	Associate Professor and Acting Chairman
Date of Birth	April 22, 1932
Degrees	B.S., Chemical Engineering, Georgia Institute of Technology, 1954 M.S., Chemical Engineering, Georgia Institute of Technology, 1956 Ph.D., Chemical Engineering, Georgia Institute of Technology, 1966

Other Academic Experience

University of Denver -- Assistant Professor, Chemical Engineering, 1967-1968.

Chemical Engineering Catholic University -- Assistant Professor, Chemical Engineering, 1966-1967. (University located in Washington, D. C.)

Georgia Institute of Technology -- Research Engineer, 1959-1965.

Other Experience

1967 to date -- Consultant in Bioastronautics to NASA.

1967 to date -- Editor, monthly review department in Water and Sewage Works.

1966 to date -- Editor, "Simulation Survey and Literature Review," monthly department of Simulation, Journal of the Simulation Councils, Inc.

1966-1968 -- Engineer and Consultant, Atlantic Research Corporation, Alexandria, Virginia.

1959-1966 -- Technical Information Section (Head, 1965-1966), Engineering Experiment Station, Georgia Institute of Technology.

1956-1959 -- Engineer, Union Carbide Chemicals Corporation, South Charleston, West Virginia.

1956 -- Lieutenant, U. S. Army, Chemical Corps, Ft. McClellan, Alabama.

Societies

American Chemical Society.

American Institute of Chemical Engineers.

Societies - (continued)

American Society for Engineering Education.

Member, Food and Biochemical Engineering Committee, AIChE (National).

Sigma Xi.

Tau Beta Pi.

Publications

"Kinetics of Diffusion-Coupled, Heterogeneous Biochemical Processes. Degradation of Cellulose by Fungi." Paper submitted to Biotechnology and Bioengineering. With D. M. Updegraff.

"On a Boundary-Value Problem Related to Air-Water Mass or Heat Transfer." Paper submitted to International Jour. Heat & Mass Transfer.

"Quasilinearization and the Estimation of Parameters in Partial Differential Equations." Paper submitted to SIAM Journal of Applied Mathematics. With V. G. Fox and K. D. Van Zanten.

"Contribution to the Theory of Trickling Filter Operation." Water Research (In press).

"Dewatering of Sludge by High-Rate Freezing at Small Temperature Differences." Environmental Science & Technology (In press). With D. M. Updegraff and C. Y. Cheng.

"Perturbation Analysis of Diffusion-Controlled Biochemical Reaction Kinetics." SIAM Journal of Applied Mathematics 19, 341-7 (Sept. 1970).

"Flow Patterns at Arterial Bifurcations." Paper presented at 63rd Annual AIChE Meeting, Chicago, November 1970. With N. S. Lynn and V. G. Fox.

"A Mechanism for the Initiation of Detonation in Hydrazine/Nitrogen Tetroxide Pulse-Mode Engine Residues." Paper presented at Western States Section, Combustion Institute, Pasadena, October 27, 1970. With W. H. McLain.

"Rocky Mountain Mine Drainage Pollution Abatement." Paper presented at AIChE Meeting, Denver, Sept. 1970. With E. B. Pugsley, D. M. Updegraff and C. Y. Cheng.

"Simulation of Air and Water Pollution Dynamics." SIMULATION 14, 165-70 (April 1970).

"Simulation of Waterway Response to Pollutant Discharges." SIMULATION 14, 95-6 (Feb. 1970).

Publications - (continued)

- "The Corrosion of Copper by Hydrogen Sulfide and Oxygen Observed by X-Ray Fluorescent Analysis." Paper presented at the 67th National AIChE Meeting, Atlanta, February 1970. With D. K. Peterson and M. T. Howerton.
- "Transient Detonation Phenomena in Pulse-Mode Rocket Engines." Paper presented at the 67th National AIChE Meeting, Atlanta, February 1970. With W. H. McLain.
- "Diffusion-Coupled Biochemical Reaction Kinetics Perturbation Analysis." Paper presented at the 62nd Annual AIChE Meeting, Washington, D. C. November 20, 1969.
- "Ignition of Compound Porous Particles with Multistage Reactions." Paper presented at the Western States Section, Combustion Institute, La Jolla, October 28, 1969. With F. I. Honea.
- "Diffusion Models for Heterogeneous Biochemical Reaction Kinetics." Bio-technology & Bioengineering 11, 719-24 (1969). With G. J. Nino.
- "Economic Study for Wastewater Treatment Plant Expansion." Public Works 100, 130-1 (Sept. 1969). With G. R. Carlson and C. Y. Cheng.
- "Management of Waste Heat Discharges of Power Facilities." Paper presented at Joint National AAS-ORSA Meeting, Denver, June 19, 1969. With N. S. Lynn.
- "Diffusion-Controlled Rate Mechanisms in Gas-Solid Reaction Systems." AIChE Journal 15, 136-7 (1969).
- "Predict Pollutants Dispersion," Hydrocarbon Processing 47, 144-150 (August 1968).
- "Research in Thermal Pollution," paper for 14th Annual Technical Meeting, Institute of Environmental Sciences, St. Louis, April 30, 1968.
- "Fluid-Dynamical Contributions to Atherosclerosis at Arterial Bifurcation Sites," paper for 8th Rocky Mountain Biomedical Symposium, Denver, May 7, 1968. With V. G. Fox
- "Reactions of Sulfur Oxides with Phosphate Rock," IEC Proc. Des. Dev. 6, 427-8 (1967). With H. C. Lewis.
- "Fluidized-Bed Reaction of Sulphur Oxides with Phosphate Rock," Sulphur (London) No. 70, 25-7 (May-June 1967). With H. C. Lewis
- "Stability of Feedback Control with Time Delay," In Systems and Process Control, pp. 105-116. Technical Manual of the AIChE (1967).

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"Sizing Up Anti-Pollution Legislation." Chemical Engineering 74, 141-6 (July 17, 1967).

"Long-Range Transport of Air Pollutants from Massive Sources," paper for 60th A.P.C.A. Meeting, Cleveland, June 14, 1967.

"Data Sources for Calculating Free Energy and Heat of Reaction," Chemical Engineering 73, 205-8 (October 10, 1966).

"Thermodynamics of Sulphur Dioxide Conversion to Sulphur Trioxide," Sulphur (London) No. 65, 37 (Sept.-Oct. 1966).

"Thermodynamics by Computer," paper for Southeast Regional AIChE Meeting, Daytona Beach, May 15, 1965. With J. H. Burson.

"Thermodynamic Functions of Nickel Carbonyl and Iron Pentacarbonyl," Jour. Chem. Eng. Data 4, 339-40 (1964). With F. H. Haynie and R. F. Hochman.

E. BIOGRAPHICAL DATA FOR DR. JOHN H. STROHL

Education B.S., Chemistry, University of Illinois, 1959
Ph.D., Chemistry, University of Wisconsin,
1964

Title Associate Professor, Department of Chemistry,
West Virginia University (Morgantown, W.
Va.)

Areas of Interest

Dr. Strohl conducted his graduate study in the area of continuous flow electrochemical cells and has since published several papers related to this. The continuous electrolysis cells he developed then have been shown to be capable of quantitative plating of metals with very short contact times and are, therefore, a suitable basis for the initial thrust of this project. His current interest has been in the development of analytical methods incorporating electrochemical principles which supports his teaching responsibilities in analytical instrumentation.

Honors

Allied Chemical Teaching Award, University of Wisconsin, 1963.

Publications

Strohl, J. H. and Polutanovich, T. A., "A Packed Graphite Cell for Thin-Layer Electrochemistry," Anal. Letters 2:423;1969.

Bamberger, R. L. and Strohl, J. H. "Quantitative Analysis of p-Nitrophenol, Hydroquinone, and p-Phenylenediamine Using Thin-Layer Chronopotentiometry," Anal. Chem. 41:1450;1969.

Strohl, J. H. and Caldwell, W., "Separation by Potential Controlled Absorption," presented at the Detroit Anachem Conference, 1970.

Strohl, J. H. and Dunlap, K. L., "Electrosorption and Chronopotentiometric Analysis of Aromatic Compounds on a Column of Graphite Particles," Pittsburgh Conference, 1972.

Blaedel, W. J. and Strohl, J. H., "Partition Chromatography by Electrodeposition in a Mercury Film," Anal. Chem. 37:64;1965.

Publications - (continued)

_____ "Continuous Quantitative Electrolysis," Anal. Chem.
36:445;1964.

_____ "Polarographic Cell for Continuous Analysis," Anal.
Chem. 36:1245;1964.